VOLUME 78

PROCEEDINGS

AMERICAN SOCIETY
OF
CIVIL ENGINEERS

DECEMBER, 1952

AMERICAN SOCIETY OF CIVIL ENGINEERS FOUNDED 1852

DEVELOPMENT OF A FLOOD-CONTROL PLAN FOR HOUSTON, TEX.

By Ellsworth I. Davis, A.M. ASCE

WATERWAYS DIVISION

Headquarters of the Society
33 W. 39th St.
New York 18, N.Y.

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Proceedings—Vol. 78 December, 1952 Separate No. 159

AMERICAN SOCIETY OF CIVIL ENGINEERS

Founded November 5, 1852

PAPERS

DEVELOPMENT OF A FLOOD-CONTROL PLAN FOR HOUSTON, TEX.

BY ELLSWORTH I. DAVIS,[1] A. M. ASCE

SYNOPSIS

In 1940 a detailed plan for the control of floods on Buffalo Bayou, which traverses Houston, Tex., was formulated by the Corps of Engineers, United States Army. Under this plan, two upstream detention reservoirs were constructed and some channel rectification was accomplished. Construction delays occasioned by World War II and the phenomenal growth of Houston have rendered the 1940 plan infeasible. Accordingly, the United States Congress in 1948 directed the chief of engineers to review the existing project and develop a new plan.

This paper describes the element of the 1940 Project Plan, the derivation of a new standard project flood, and two basic plans that were considered in the investigations. One basic plan provides for the diversion of most of the floodwaters into another watershed—the Brazos River. The other plan relies upon rectification of the principal channels in the Buffalo Bayou watershed to pass peak discharges without appreciable damage. As a result of the investigation, it was concluded that the channel rectification plan was more economically justified.

THE FLOOD-CONTROL PROBLEM AT HOUSTON

The New Orleans Flood Problem.—The two principal cities on the coast of the Gulf of Mexico, New Orleans (La.) and Houston, have one problem in common—floods. However, the causes and characteristics of their floods have nothing in common. People in the United States are somewhat familiar with the problem confronting New Orleans. The Mississippi River, draining approximately 1,244,000 sq miles (or 40% of the United States), from the Alleghenies to the Rockies, flows past its door. The runoff from a storm on a

NOTE.—Written comments are invited for publication; the last discussion should be submitted by June 1, 1953.

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tributary watershed 1,000 miles away will finally make its way past New Orleans, and if superimposed upon flood runoffs from other tributary streams, creates a flood condition at New Orleans. The floods are slow to rise and slow to fall, and their crests are predictable days and even weeks in advance. Since the record flood of 1927, the city has been further protected by the raising and strengthening of its levees, by the construction of floodways to divert floodwaters to the Gulf through Lake Pontchartrain and through the Atchafalaya Basin, and by the construction of reservoirs on the headwaters of tributary rivers. In short, the flood problem at New Orleans is national in character. The flood discharges are enormous, but are predictable so that ample time is provided for placing into effect the required components of its flood-control system.

The Houston Flood Problem.—On the other hand, Houston's flood problem, although just as acute, is very local in character. Buffalo Bayou, a small stream virtually unknown outside of Harris County, Texas, is the offender. Its drainage area just below its confluence with Brays Bayou is only 626 sq miles. Houston floods, therefore, are the result of local storms. These storms are of high intensity and are unpredictable. Since the topography is flat and there are few adequate natural drainage channels, the essential ingredients of a flood are constantly present.

Buffalo Bayou is important to Houston not only because it is the principal drainage channel, but also because the lower reaches, above the junction with the San Jacinto River, have been dredged to form the upper portion of the Houston Ship Channel and the turning basin of the Port of Houston. Floods on Buffalo Bayou, therefore, can inconvenience and delay shipping by causing excessive current velocities and depositing silt in the ship channel and turning basin. Any plan for the control of floods in Houston and its environs consequently must consider these current velocities and silt deposits.

Description of Buffalo Bayou Watershed

Buffalo Bayou (Fig. 1) rises in eastern Waller County and western Harris County, flows generally eastward in a narrow and tortuous channel 75 miles long, passes through the City of Houston, and enters the San Jacinto River 9 miles above Galveston Bay. The lower reaches of the bayou, as previously mentioned, have been improved as a part of the Houston Ship Channel, which affords deep draft ocean navigation to extensive terminal developments in and below Houston. The authorized project depth of the channel is 36 ft, through Galveston Bay to the Gulf.

The watershed of Buffalo Bayou lies entirely within a broad, almost featureless plain that rises gently toward the northwest with a slope of about 3 to 7 ft per mile. Surface soils consist essentially of fine sand loam and clay that are poorly drained and do not permit much percolation of surface water.

The streams in the Buffalo Bayou watershed have little or no flow during a considerable portion of the year, but are subject to high flood stages resulting from surface runoff during storms. The stream channels are small and the divides between drainage areas are not clearly defined. Consequently, during

heavy rainstorms, the streams overflow their banks and push generally southward across the divides from one watershed to the next.

Buffalo Bayou is joined in the commercial district of Houston by White Oak Bayou. Brays and Sims bayous, which pass through residential areas,

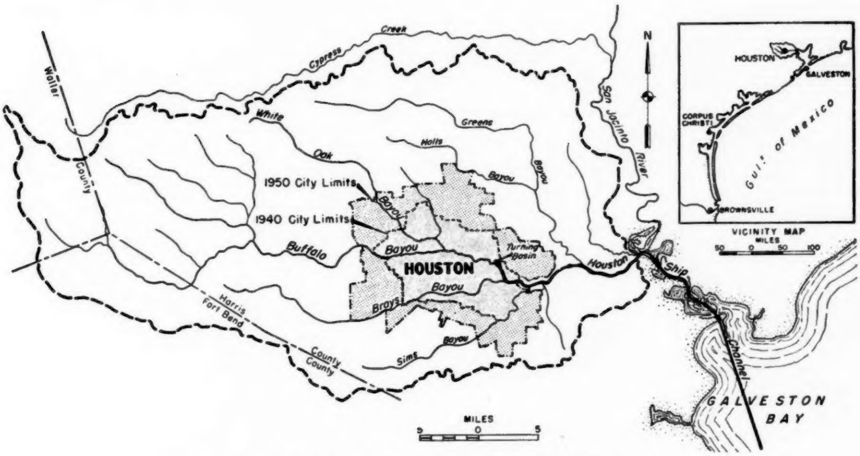

Fig. 1.—Map of Buffalo Bayou Watershed

also enter the main stream within the city. The increasing value of lands in the commercial area of the city has resulted in encroachment upon the flood plain of Buffalo Bayou by building adjacent to the channel and even over it.

Authorization of 1940 Flood-Control Plan for Buffalo Bayou

Following the disastrous Buffalo Bayou flood of December, 1935, Congress directed the chief of engineers to investigate and submit a report on a plan to improve the Houston Ship Channel, to protect it from siltation, and to provide flood control on Buffalo Bayou and its tributaries. This report was prepared by the Galveston District of the Corps of Engineers and was submitted in April, 1937. The project as proposed in the report was authorized by Congress in 1938 and modified as to terms of local cooperation in 1939. Based upon this authorization, the Galveston District, in 1940, prepared a more detailed plan for flood control on Buffalo Bayou and its tributaries above the turning basin. This plan constitutes the authorized project plan.

Selection of Design Storm for the 1940 Project Plan

In order to determine the most severe storm to be expected in the basin, fifty-two storms in central and coastal Texas were investigated. Of these, three storms were selected in the development of a design storm for the project. These storms were as follows:

Storm of June 27 to July 1, 1899.—This storm, which centered at Hearne, Tex., produced greater depths over a larger area than any other storm of record

in the United States (see Fig. 2). The maximum depth of this storm was 31.4 in. in a period of three days, and the average depth over an area of 1,000 sq miles was 25.8 in.

Storm of September 6 to 10, 1921.—According to the United States Weather Bureau, the greatest 24-hr rainfall ever recorded in the United States occurred at Taylor, Tex., September 9 to 10, 1921, when 23.11 in. fell in 24 hr. In many

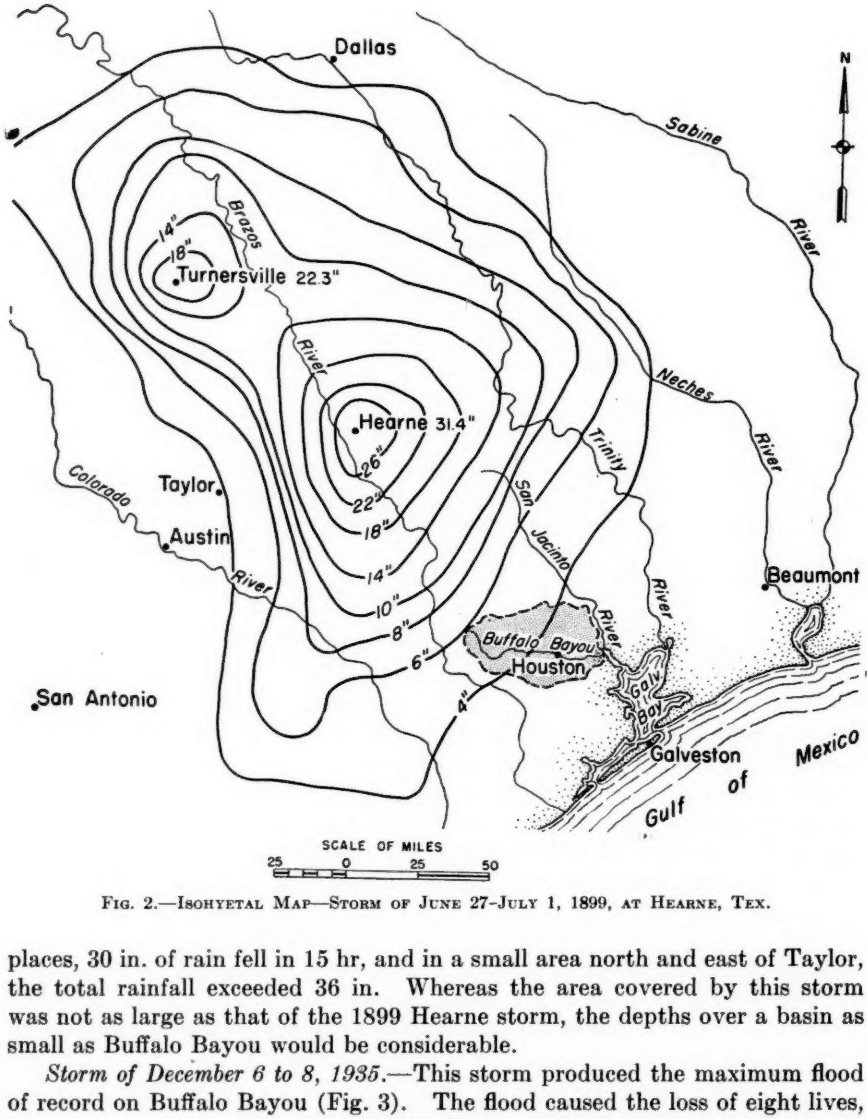

FIG. 2.—ISOHYETAL MAP—STORM OF JUNE 27–JULY 1, 1899, AT HEARNE, TEX.

places, 30 in. of rain fell in 15 hr, and in a small area north and east of Taylor, the total rainfall exceeded 36 in. Whereas the area covered by this storm was not as large as that of the 1899 Hearne storm, the depths over a basin as small as Buffalo Bayou would be considerable.

Storm of December 6 to 8, 1935.—This storm produced the maximum flood of record on Buffalo Bayou (Fig. 3). The flood caused the loss of eight lives, property damage estimated at $2,529,000, and the stoppage of traffic to the

Port of Houston for three days because of excessive currents in the ship channel. The storm produced an average rainfall depth of 14.8 in. on the watershed above the confluence of Buffalo and White Oak bayous, and resulted in peak flows as shown in Table 1, Col. 2. During this flood some overflow occurred from White Oak Bayou into Buffalo Bayou, and considerable overflow occurred from Buffalo Bayou into Brays Bayou.

The Hearne storm of 1899, which centered only 90 miles from Houston, was used as a basis in developing the design storm. The possibility of intensities or rainfall greater than those recorded or indicated for the Hearne storm led to the inclusion of rates of rainfall recorded at the Taylor storm of 1921. The resulting rainfall used for design consisted of a maximum depth of 31.4 in. in a period of three days, using the storm pattern of the 1899 storm superimposed upon the basin. It was assumed that the axis of the storm could be rotated in any direction. Peak flows produced by the design storm are shown in Table 1, Col. 3. The flows shown in Table 1 are those that would be pro-

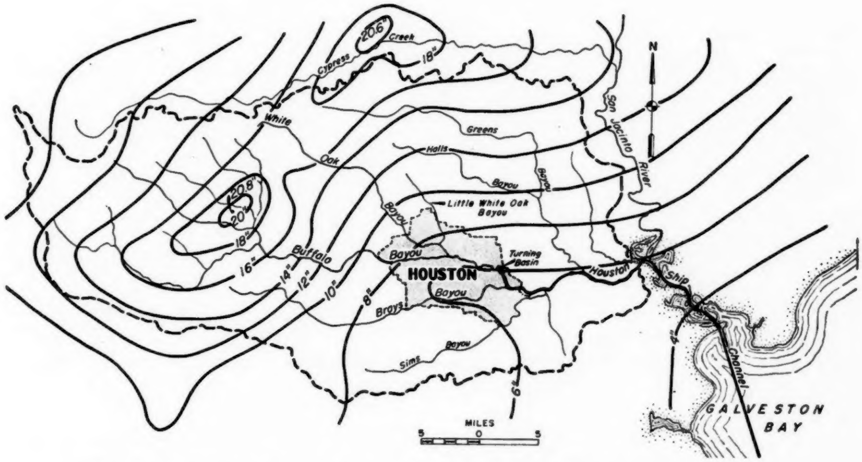

FIG. 3.—ISOHYETAL MAP—STORM OF DECEMBER 6–8, 1935, ON BUFFALO BAYOU

duced provided that overflows from one drainage basin into the next were prevented. Since considerable overflow normally takes place, these figures represent potential flows.

Local interests stated that, although ultimate protection against the design storm was desirable, they would be satisfied initially with construction that would provide protection against a lesser flood. They expressed satisfaction with protection against a storm that would develop runoffs 50% greater than those following the 1935 storm. For purposes of computation, the Corps of Engineers used the design storm for the design of the reservoirs of the flood-control plan and the storm of 1935 increased 50%, for the design of the portion of the system below the reservoirs. The 1935 storm increased 50% was transposed to critical locations in order to determine the worst flood conditions for

this rainfall. The peak flows that would be produced by this storm are shown in Table 1, Col. 4.

Development of the 1940 Project Plan

In the development of the 1940 Project Plan for flood control of Buffalo Bayou, plans for channel rectification and enlargement, regulation, and diversion were investigated. The plan as finally evolved consisted essentially of a

TABLE 1.—Peak Flow Data in Cubic Feet per Second

Location	Storm of Dec. 6–8, 1935	Design storm for 1940 Project Plan	1935 storm increased 50%	1940 Project Plan in Operation [a]			Conditions Existing in 1951		New Project Flood Plans [c]	
				1935 storm	1935 storm[b]	Design storm	Standard project storm	1935 storm [b]	Diversion plan	Channel rectification plan
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
White Oak Bayou										
Above[d]	...	22,700	19,300	2.6	7.4	8.5	...	...	...	...
At mouth	16,750	27,600	23,500	5.6	14.8	17.5	25,200	24,700	12,400	25,200
Buffalo Bayou										
Above[e]	40,000	84,700	60,000	8.4	19.5	24.3	26,400	22,500	27,600	26,400
Below[e]	53,000	104,400	79,500	13.6	32.8	40.7	49,200	46,200	34,300	49,200
Below[f]	...	...	...	...	...	...	74,000	70,700	52,700	74,000
Brays Bayou										
Below[g]	...	...	...	...	...	...	16,200	17,800	0	16,200
At USGS Gage	...	...	...	...	...	...	25,000	24,600	15,800	25,000
At mouth	...	...	...	...	...	...	31,200	30,700	23,000	31,200

[a] In thousands of cubic feet per second. [b] Increased 50%. [c] Comparison of peak flows of standard project flood with diversion and channel rectification plans in operation. [d] Above Little White Oak Bayou. [e] Above or below mouth of White Oak Bayou. [f] Below Brays Bayou. [g] Below Kegans Bayou.

detention and diversion system. Principal features of the plan are as follows (Fig. 4):

1. White Oak Reservoir.—A storage basin of such magnitude as to prevent runoff produced by the design storm on the upper watershed of White Oak Bayou from entering the city.
2. By-pass Channel.—Designed to divert to Buffalo Bayou the runoff that is produced on a small portion of the White Oak Bayou watershed that lies outside of White Oak Reservoir and would otherwise be undrained.
3. North Canal.—A waterway to divert the floodwaters entering White Oak Reservoir into the San Jacinto River.
4. Addicks and Barker Reservoirs.—On Buffalo Bayou and tributaries, detention basins of such magnitude as to limit the runoff produced by the design storm to a maximum total regulated discharge of about 15,000 cu ft per sec.
5. Cypress Creek Levee.—To prevent overflow into Addicks Reservoir.
6. Rectification of Buffalo Bayou.—From Addicks and Barker reservoirs to the entrance of South Canal, to accommodate the maximum outflow from these reservoirs.

7. Interception Dam on Buffalo Bayou.—West of the city limits, to divert flood flows from this bayou into South Canal.

8. South Canal.—A channel of sufficient capacity to divert to Galveston Bay the regulated discharge from Addicks and Barker reservoirs, and a large portion of the flows from the uncontrolled areas west and south of them.

9. Removal of Encroachments in Buffalo Bayou.—Within the city, to provide protection against the runoff that would be produced below White Oak Reservoir and the interception dam on Buffalo Bayou by a storm as large as the 1935 storm increased 50%.

The peak flows (with all the features of the 1940 Project Plan in operation) that would be produced with a recurrence of the 1935 storm, the 1935 storm increased 50%, and the design storm are shown in Table 1, Cols. 5, 6, and 7. The latter two storms are centered in positions below Addicks and Barker reservoirs to produce maximum peak flows.

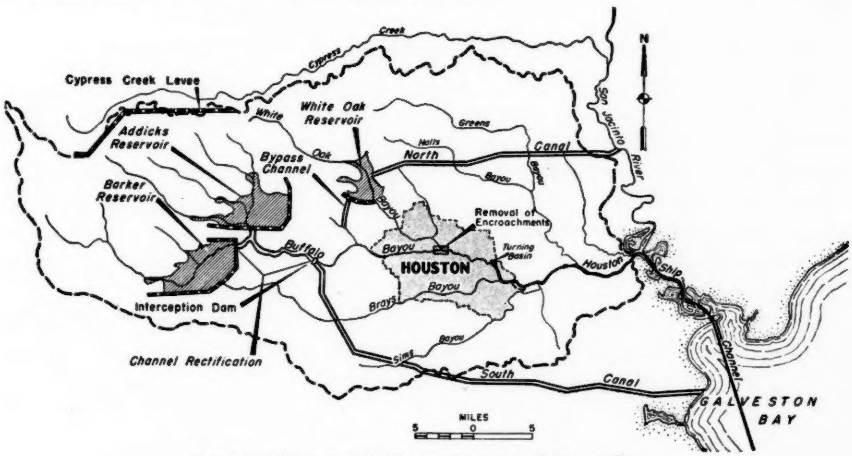

Fig. 4.—Map of 1940 Flood-Control Project Plan

The only items of the 1940 Project Plan that have been completed are: (*a*) Addicks Reservoir, increased in size to eliminate the need for the Cypress Creek Levee; (*b*) Barker Reservoir; and (*c*) rectification of Buffalo Bayou downstream from the two reservoirs for a distance of 6.2 miles. These projects were completed in 1948.

Need for a New Project Plan

Growth of Area.—The project plan was drawn up in 1940. Since that time World War II has been fought and new industries, based on newly discovered petroleum and natural gas supplies, have been developed in the Houston area. Houston, by virtue of its near-by and easily developed natural resources, its accessibility to markets through an extensive rail network, the Houston Ship Channel, and the Gulf Intracoastal Waterway, has grown vigorously. Its population increased 54% from approximately 385,000 in 1940 to 594,000 in 1950. The site selected for the White Oak Reservoir is now within the city

limits and is in a residential area. Residential areas also cover considerable portions of the rights of way of the proposed North and South canals. Furthermore, the original plan provided for protection of only that portion of the watershed above the turning basin of the Houston Ship Channel. Since the war, there has been extensive development along the ship channel below the turning basin and also along Brays Bayou, which was not considered in the initial report because it enters Buffalo Bayou below the turning basin. Brays Bayou has been the site of one of the greatest concentrations of residential and hospital development within the city. As a consequence, it is no longer feasible to complete the remaining elements of the original project plan.

In view of the foregoing facts, Congress, in 1948, directed the chief of engineers to review the 1940 authorized project and to develop a comprehensive plan for the control of floods throughout the entire Buffalo Bayou watershed. The Galveston District of the Southwestern Division of the Corps of Engineers made this review examination and survey.

Determination of Standard Project Flood for New Project Plan

Definition of Terms.—As the result of additional experience and study since 1940, and in order to achieve more uniform results in the hydrological investigations of its field agencies, the Corps of Engineers has developed the concept of a standard project storm and a standard project flood for its flood-control investigations. A standard project storm for a particular drainage area is the most severe flood-producing rainfall quantity-intensity sequence relationship and areal distribution of any storm that is considered reasonably characteristic of the region in which the drainage basin is located.

The standard project flood is the runoff from the standard project storm. The standard project flood represents a practical measure of the "flood potentiality" of a particular drainage basin, corresponding to storms and runoff conditions observed in the region on a sufficient number of occasions to demonstrate that a distinct danger exists of such a flood occurrence. The standard project flood reflects a generalized analysis of flood potentialities in a region, as contrasted to an analysis of limited flood records at the specific locality that may be misleading because of the inadequacies of records or abnormal sequences of hydrologic events. The statistical probability of occurrence of this standard project flood is not of primary importance. The principal purposes of the standard project flood are to: (*a*) Serve as a "standard" against which the degree of protection finally selected for the project may be judged and compared with protection provided at other projects of a similar nature; and (*b*) represent the flood discharge that should be selected as the design flood for the project, or approached as nearly as practicable in consideration of economic or other governing limitations, if an unusually high degree of protection is justified by hazards to life and high property values within the area to be protected.

Basis of Standard Project Flood.—The standard project flood used in the 1951 investigation of Buffalo Bayou is derived from an over-all study, by the Corps of Engineers, of all recorded major storms in the United States east of the 105th meridian for small drainage basins of 1,000 sq miles or less. The 105th meridian crosses the extreme western tip of the State of Texas and

Buffalo Bayou therefore falls within the area encompassed by this study. The rainfall criteria used in the over-all study are based primarily on an analysis of major convective-type storms and relate to a total storm duration period of 24 hr. The average depth over an area of 200 sq miles for a duration period of 24 hr was used as the unit for comparing and correlating the storms.

The average depths of 24-hr rainfall over an area of 200 sq miles for all storms that have been investigated to date were plotted in their geographical positions. Generalized isohyets representing maximum possible 24-hr rainfall over 200 sq miles were obtained from the Weather Bureau and superimposed over this map. Studies of the relationship between maximum possible rainfall and the major storms of record indicated that, in general, 50% of maximum possible rainfall includes all but about 15% of the major storms of record. Accordingly, 50% of the maximum possible rainfall in the vicinity under consideration was adopted for the standard project storm.

Selection of Rainfall Pattern.—The areal distribution of the standard project storm is determined by selecting one of four typical rainfall isohyetal patterns:

Pattern	Shape
A	Ellipse
B	Pear or tear shaped
C	Elongated and flattened ellipse
D	Similar to Pattern B except that it is elongated and flattened

The pattern is selected that gives the greatest yield when "fitted" over the watershed under investigation. Pattern B was selected for application to the Buffalo Bayou watershed since it created the greatest peak runoff. These patterns all have the same isohyetal depth values for corresponding isohyetal lines, varying from a maximum of 12 in. downward, and are adjusted to the standard project storm pattern by a constant additive value. For the Buffalo Bayou standard project storm, this value is 9.0 in. Fig. 5 shows the standard project storm as thus determined, fitted over the Buffalo Bayou watershed below Addicks and Barker reservoirs.

After fitting the standard project storm over the section of the watershed being studied, to give the maximum peak discharges, the total 24-hr storm volume is determined in the usual way, by planimetering the isohyetal patterns and determining the average depth of storm rainfall. This storm rainfall depth is then divided into four 6-hr periods in accordance with percentages determined in the over-all study. The Buffalo Bayou standard project storm has an average depth of 19 in. over 200 sq miles in 24 hr. For this depth, the time distribution of rainfall for the four 6-hr periods is as follows:

Period	Percentage of rainfall
First	9.5
Second	20.1
Third	56.7
Fourth	13.7

Infiltration losses of 1.0 in. for the first 6-hr period, and 0.6 in. for each of the three remaining 6-hr periods were then subtracted to obtain the rainfall excess. The rainfall excess was then developed into the standard project flood by means of the Snyder unit hydrograph method.[2] The coefficients used in this formula were determined from the reproduction of actual floods on Buffalo Bayou and tributaries.

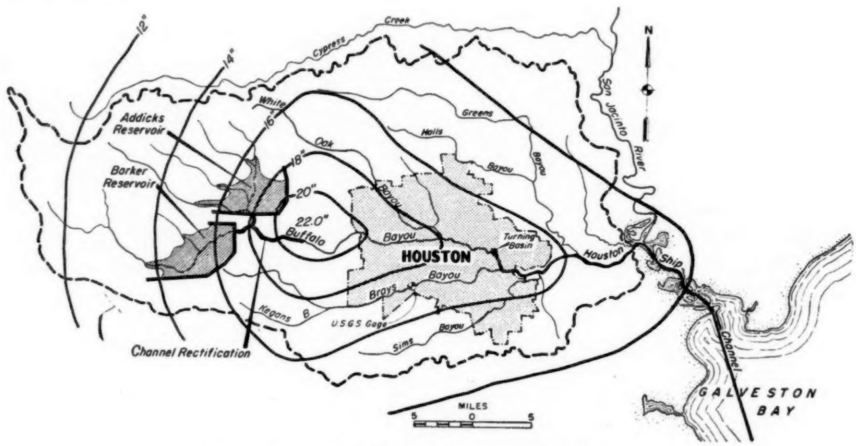

FIG. 5.—ISOHYETAL MAP OF STANDARD PROJECT STORM

The peak flows that would be produced by the standard project storm fitted over the principal parts of the Buffalo Bayou watershed, under conditions existing in 1951, with Addicks and Barker reservoirs in operation, are shown in Table 1, Cols. 8 and 9. For comparison, the peak flows that would be produced by the 1935 storm increased 50% are also shown.

PLANS OF IMPROVEMENT CONSIDERED

In an endeavor to expedite the preparation of a report that would provide a solution for the most pressing flood problems of Houston, consideration of the flood problems on the tributary streams that do not appreciably affect Houston, such as Sims, Halls, and Greens bayous was postponed. The resultant interim report, consequently, covers only Buffalo Bayou itself and its two principal tributaries, White Oak Bayou and Brays Bayou.

Of the numerous general plans of improvement considered, two have shown the greatest possibilities of providing flood protection at a justifiable cost. The first of these plans calls for the diversion of the bulk of the floodwaters to the Brazos River; the second provides for rectification of existing channels to pass safely the standard project flood.

DIVERSION PLAN

The basic aspect of the diversion plan (Fig. 6) is the routing of floodwaters from the upper reaches of Buffalo and Brays bayous through an artificial

[2] "Synthetic Unit Graphs," by Franklin F. Snyder, *Transactions*, Am. Geophysical Union, Part IV, 1939, pp. 725–738.

channel to the Brazos River. The plan utilizes the storage effects of Addicks and Barker reservoirs, which were constructed under the 1940 Project Plan. Its main features are as follows: Addicks Reservoir; Barker Reservoir; diversion canal from Buffalo Bayou to the Brazos River, 18 miles long; diversion canal from White Oak Bayou to Buffalo Bayou, 7 miles long; rectification of Brays Bayou; and rectification of Buffalo Bayou.

The Buffalo Bayou-Brazos River diversion canal would divert from Buffalo Bayou the flood discharges from the uncontrolled drainage area below Addicks and Barker reservoirs as well as the releases from these reservoirs, thereby reducing the amount of channel rectification required for Buffalo Bayou. The diversion canal would also intercept runoff from the upper portion of the Brays Bayou watershed, thus reducing the cost of rectifying Brays Bayou farther downstream.

The White Oak Bayou-Buffalo Bayou diversion canal, by diverting floodwaters from the upper reaches of White Oak Bayou, would eliminate the necessity for improving White Oak Bayou. Peak flows of the standard project flood, with the diversion plan in operation, are shown in Table 1, Col. 10.

The principal advantage of the diversion plan is that, by routing the floodwaters around the city, rather than through it, the need for expensive rights of way through the highly developed portions of the city and for the removal or alteration of obstructive structures such as buildings and bridges would be substantially eliminated. Flood interference with the operation of the Houston Ship Channel would be reduced, but would be so very infrequent, after the channel has been enlarged to its authorized dimensions, that this advantage is relatively unimportant.

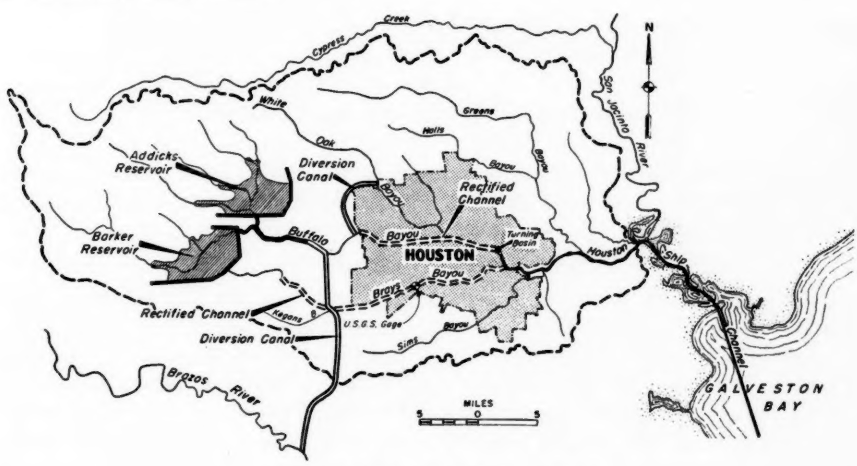

FIG. 6.—MAP OF DIVERSION PLAN

Opposed to these advantages are the difficulty and expense of maintaining two artificial diversion canals having a combined length of 25 miles. Experience has shown that, with the high annual rainfall in the area and the long growing season, channels are quickly grown up in weeds which, of course,

effectively reduce channel discharge capacity. The diversion canals would also necessitate the construction of several highway and railroad bridges, pipe-line crossings, and siphons for irrigation ditches. Another disadvantage of the diversion plan is that the Brazos River could be in flood at the same time that floodwaters from the Buffalo Bayou watershed were being discharged through the diversion canal to the Brazos River. In such an event flood damages along the Brazos would be increased. Furthermore, the capacity of the diversion canal would be reduced as a result of the backwater effect. In fact, it is possible that the water from the Brazos River in flood could back up into the Buffalo Bayou watershed through the diversion canal thus adding to the magnitude of the flood along Buffalo Bayou. A further difficulty of this proposed plan is a legal one arising from the diversion of water from one

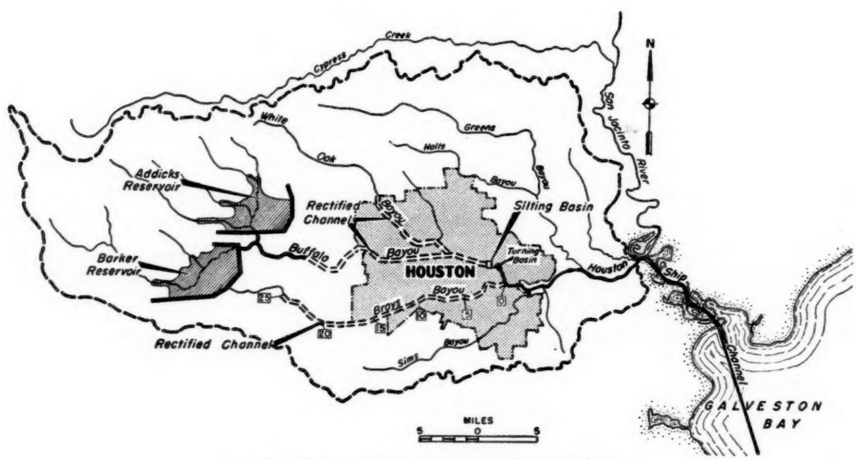

Fig. 7.—Map of Channel Rectification Plan

watershed into another. This is a problem for which local interests would have to give adequate assurances of cooperation before any federal project could be initiated.

Channel Rectification Plan

The other basic plan considered (Fig. 7) involves Addicks Reservoir and Barker Reservoir, the rectification of Buffalo, White Oak, and Brays Bayous so they would carry within their banks the runoff from the standard project storm as regulated by Addicks and Barker reservoirs, and the dredging of a silting basin immediately upstream of the turning basin to reduce the amount of silt deposit in the turning basin and the ship channel. Peak flows of the standard project flood with this plan in operation are compared with those of the diversion plan in Table 1, Cols. 10 and 11.

The principal advantage of this plan is the elimination of the two artificial diversion canals required by the diversion plan. The elimination of these channels would result in a substantial reduction in maintenance since only the rectified natural channels would have to be maintained. The legal complica-

tions of diverting water from one watershed to another would also be eliminated.

Disadvantages of the plan are that it would necessitate the removal or alteration of a substantial number of existing installations, including buildings and bridges, and would require very costly rights of way, particularly through the highly developed commercial and residential portions of the city. Another problem is that of disposing of approximately 8,100,000 cu yd of material excavated from within the city. The foregoing disadvantages could be overcome to a large extent by lining the channels to permit the use of smaller cross sections having the same discharge capacities. Comparison of the over-all costs of channel rectification, with and without lining, show that on White Oak Bayou and portions of Brays Bayou, channel lining is justified.

Flood discharges would interfere with barge navigation on the Houston Ship Channel somewhat more frequently than with the diversion plan. Interference with ocean-going vessels would, however, be so very infrequent as not to constitute a serious drawback.

Progress of Investigation

Each of the two plans would be equally effective in controlling floods in the Houston area, and the benefits arising from the control of these floods apparently exceed the cost of either plan. Selection of the plan for control of floods on Buffalo Bayou and its two principal tributaries that flow through Houston was based on a comparison of yearly costs (including amortization and interest on first cost and maintenance). Interference with navigation on the Houston Ship Channel in either plan will be so infrequent that there appears to be little justification for favoring one plan over the other in this respect.

The remainder of this paper outlines some of the problems that were considered and analyzed in the investigation.

Effects of High Stages on the Brazos River on the Operation of the Diversion Plan.—The diversion plan presents some relatively serious hydraulic problems. The Buffalo Bayou-Brazos River diversion canal will cut through the natural ridge or watershed divide that confines floodwaters on the Brazos River to the Brazos River watershed. If this natural protective ridge is breached by the canal, extreme floods, such as that of 1913 on the Brazos, will flow through the opening and flood extensive areas along Brays and Buffalo bayous, particularly along the former. Flooding of the area between the Brazos River and Buffalo Bayou could be prevented by levees along the banks of the diversion canal and along upper Brays and Buffalo bayous, with outlet structures for minor tributaries. However, if the upper reaches of Brays Bayou or Buffalo Bayou were in flood, the resulting flooding in those areas would be considerably more severe since the flows would be affected by the Brazos River backwater in the diversion canal.

Examination of past rainfall over the Buffalo Bayou watershed in the area above the diversion canal to the Brazos River, and of coincident past floods on the Brazos River, reveals that once in about every 3 to 5 years Brays and Buffalo bayous would be discharging into the Brazos River when the Brazos River is above flood stage, resulting from either runoff from its own watershed or in combination with discharge from Brays and Buffalo bayous. The average

annual damage on Buffalo and Brays bayous because of backwater from the Brazos River, and the damage to the Brazos River watershed as a result of discharges from the diversion canal would be subtracted from the benefits arising from the diversion plan.

Effects on Navigation in the Houston Ship Channel of the Diversion and Channel Rectification Plans.—Any plan for the control of floods in the Buffalo

TABLE 2.—ESTIMATED FREQUENCY OF CURRENT VELOCITIES IN THE HOUSTON SHIP CHANNEL

Current velocity (miles per hr)	FREQUENCY OF CURRENT VELOCITIES IN YEARS		
	1951 conditions	Diversion plan	Channel rectification plan
2	3	43	8
4	37	1,000	500
7	1,000	1,000	1,000

Bayou watershed must not create excessive currents in the Houston Ship Channel that would stop or otherwise seriously interfere with maritime traffic. The 1935 flood (the maximum flood of record on Buffalo Bayou) stopped traffic for three days. However, at that time, the channel immediately below the turning basin had been dredged to a depth of only 30 ft and a bottom width of 150 ft. In 1951, the authorized depth was 36 ft with a bottom width of 300 ft, providing a cross-sectional area of channel approximately 84% larger than in 1935. Furthermore, Addicks and Barker reservoirs have been con-

TABLE 3.—ESTIMATED DURATION OF CURRENT VELOCITIES IN THE HOUSTON SHIP CHANNEL

Frequencies (years)	DURATION OF CURRENT VELOCITIES IN HOURS								
	Current velocities								
	2	4	7	2	4	7	2	4	7
	1951 conditions			Diversion plan			Channel rectification plan		
5	33	0	0	0	0	0	0	0	0
10	43	0	0	0	0	0	17	0	0
25	55	0	0	0	0	0	31	0	0
50	62	14	0	6	0	0	39	0	0
100	67	23	0	16	0	0	45	0	0

structed and they reduce the discharge and, consequently, the velocities through the ship channel.

Table 2 shows the estimated frequency at which current velocities in the Houston Ship Channel could be expected to occur under 1951 conditions and with the diversion and channel rectification plans in effect. Frequencies shown for diversion and channel rectification plans are based on the assumption that

the channel has been dredged to authorized dimensions. Frequencies shown under "1951 Conditions" are based on actual channel dimensions at that time.

Table 3 shows the estimated duration, in hours, of current velocities, in the Houston Ship Channel, through a frequency range of from 5 yr to 100 yr, under 1951 conditions and with the diversion and channel rectification plans in effect.

From Tables 2 and 3 it may be seen that, under either plan, interference with ocean-going ship traffic would be negligible. Since the tow boats used for barge transportation along the Texas Gulf Coast usually have less than 400 hp, interference with barge traffic would be somewhat greater. However, this traffic is more flexible because of its shorter haul distances, and its fixed operting expenses are less than for ocean traffic. Consequently, interference with barge traffic would be relatively insignificant under either plan.

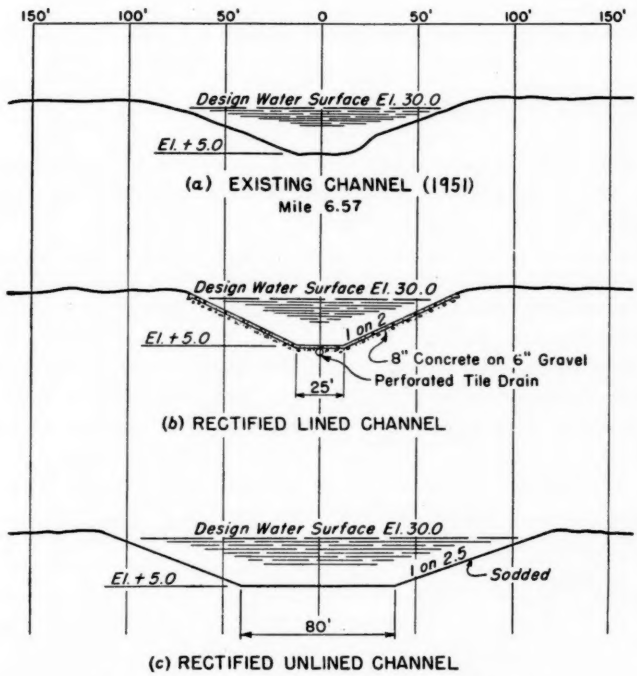

Fig. 8.—Typical Cross Sections of Brays Bayou

Comparison of Lined Channels versus Unlined Channels Through Costly Rights of Way.—Because of the high cost of real estate and of the modifications to bridges and other structures required for the channel rectification plan, consideration was given to lining the channels to reduce the channel cross section, and, consequently, the requirements for real estate, bridge widening, and modifications to structures. Lined channels have the further advantage of lowering annual channel maintenance costs. In addition, channel lining of Buffalo and White Oak bayous would largely eliminate the scouring effects of

the floodwaters and make unnecessary the silting basin upstream from the turning basin of the ship channel.

The effectiveness of channel lining in reducing the width of the rectified channel of Brays Bayou is shown in Figs. 8 and 9. It may be seen from Fig. 9 that, for the channel rectification plan, the reduction in top width varies from approximately 100 ft near the upper end of the project to approximately

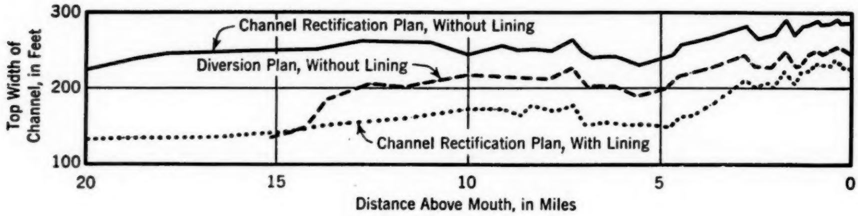

FIG. 9.—PROFILE OF BRAYS BAYOU

50 ft near the mouth of the bayou. In fact, as shown in Fig. 9, Brays Bayou, if lined for the channel rectification plan, is narrower than the unlined rectified channel of the diversion plan.

The studies of costs of several plans of channel rectification showed that partial lining of the bottom and lower portions of the sides of Brays Bayou would retain most of the advantages of full channel lining and would, of course, be more economical.

There are fewer advantages for lining Buffalo Bayou than for Brays Bayou. Between the turning basin and the mouth of White Oak Bayou, only 1,800,000 cu yd of material would have to be removed. The channel section in this

TABLE 4.—ESTIMATED EXCAVATION QUANTITIES FOR CHANNEL RECTIFICATION PLAN

Channel	Channel Excavation, in Cubic Yards	
	Capable of being disposed of alongside channel	Requiring transportation to spoil areas
Buffalo Bayou	5,300,000	1,800,000
Brays Bayou	5,300,000	6,300,000
White Oak Bayou	2,100,000	0
Totals	12,700,000	8,100,000
Total excavation	20,800,000	

reach is generally adequate, the required work consisting essentially of trimming occasional restrictions and providing bulkheads or retaining walls for the local treatment of encroaching structures and improvements. Above the mouth of White Oak Bayou, the channel of Buffalo Bayou is adequate. Rectification in this area would consist of cutting through circuitous bends in the channel. The 5,300,000 cu yd of material so removed would be placed in the abandoned

river bends. Channel lining is not economically justified, therefore, on Buffalo Bayou.

White Oak Bayou, on the other hand, requires lining because of its steep slope, which averages 3.7 ft per mile on the rectified alinement. For the standard project flood, velocities as high as 10 ft per sec in an unlined rectified

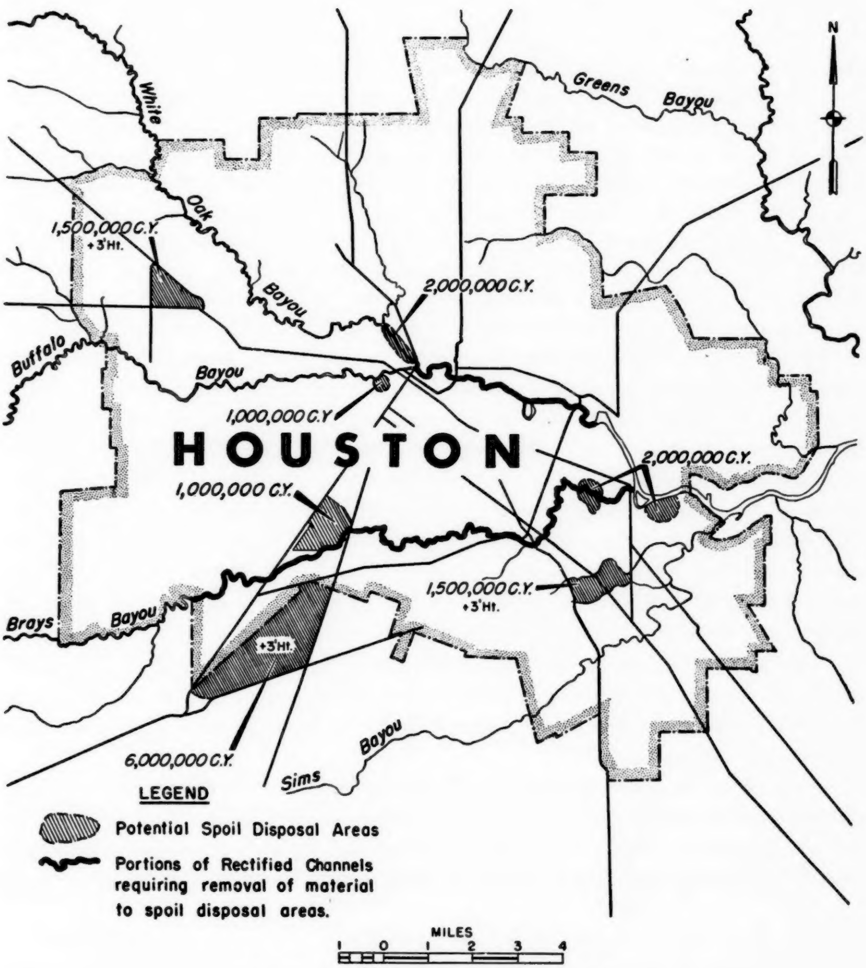

Fig. 10.—Potential Spoil Disposal Areas

channel would result. These velocities would cause excessive scour unless the channel were lined.

Disposition of Large Amounts of Spoil Excavated Within City Limits.—Under the channel rectification plan, assuming that Buffalo and Brays bayous are not lined, approximately 20,800,000 cu yd of material would have to be ex-

cavated in widening, deepening, and straightening Buffalo, Brays, and White Oak bayous. From Table 4 it may be seen that, of this amount, 12,700,000 cu yd could be deposited alongside the bayous or in bends that have been cut off and abandoned as a result of channel straightening. The disposal of this material could be done with conventional, heavy earth-moving equipment and, consequently, creates no unusual problem. The remaining 8,100,000 cu yd, however, would have to be transported through city streets to suitable disposal areas. It should be noted that none of the material excavated from White Oak Bayou would require transportation to spoil areas.

The disposition of 8,100,000 cu yd of material excavated from within the city limits constitutes a rather unique problem. This fill, if placed in a spoil disposal area of 250 city blocks (2.5 acres per block), would be approximately 8 ft high. In an area as devoid of topographic relief as Houston, such a spoil bank would probably be a distinct asset from a real estate development viewpoint. However, the possibilities of this cannot be explored until the excavation is actually made. Consequently, unit costs used in estimates do not include any credit for such land enhancement.

The development of reasonably accurate unit costs for the excavation of 8,100,000 cu yd of material and its removal by truck from the vicinity of the channels is dependent on locating adequate spoil disposal areas in or near the city. Reconnaissances on the ground, supplemented by the use of aerial photographs, disclosed suitable areas, as shown in Fig. 10, whose capacities exceed the requirements. Use of these areas has not been confirmed at this stage of the investigation, nor do the areas indicate all the possible ones. Furthermore, it is quite possible that a substantial portion of the 8,100,000 cu yd could be deposited locally in low spots or in old bayou bends that are cut off in the channel straightening. However, reconnaisances do indicate generally the availability of adequate disposal areas.

The maximum length of haul to the areas shown in Fig. 10 is 2.5 miles. However, to provide for the possibility that all the areas might not be available when the project is under construction, an average haul of 5 miles was used in the estimates.

As a result of these studies and investigations, it was concluded that the channel rectification plan would be more economically justified to provide for the control of floods on Buffalo Bayou and its two principal tributaries that flow through the City of Houston, than would the diversion plan.

Acknowledgments

The writer, as district engineer of the Galveston District, Corps of Engineers, under whom the investigation was conducted, had general supervision over the project. Information and data used in this paper were derived largely from the following:

Kenneth Heagy (M.ASCE), chief, Engineering Division, Galveston District; E. A. Weiser, chief of the Buffalo Bayou Report Section, and E. H. Brown, chief of the Hydraulics and Hydrology Section, both being under the

general supervision of A. B. Davis, Jr., chief of the Planning and Reports Branch, Engineering Division, Galveston District; K. V. Speeg (A.M.ASCE), Fort Worth District, Corps of Engineers; and Albert L. Cochran (M. ASCE), Office, Chief of Engineers. In addition, information was obtained from Howard Jensen, engineer for the Harris County Flood Control District, and Henry R. Norman (M.ASCE), consultant to the Harris County Flood Control District.

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